Parton Distributions and Spin-Orbital Correlations

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In this talk, I summarize a recent study showing that the large-x parton distributions contain important information on the quark orbital angular momentum of nucleon. This contribution could explain the conflict between the experimental data and the theory predictions for the polarized quark distributions. Future experiments at JLab shall provide further test for our predictions.

Keywords: Quark Orbital Angular Momentum; Large-x Parton Distributions

1. Introduction

Power-counting rules for the large-x parton distributions were derived many years ago based on perturbative quantum chromodynamics (pQCD) combined with a S-wave quark model of hadrons.[1–4] The basic argument is that when the valence quark carries nearly all of the longitudinal momentum of the hadron, the relevant QCD configurations in the hadronic wave function become far off-shell and can be treated in pQCD. The power-counting rule has also been generalized to sea quarks, gluons, helicity-dependent distributions,[5,6] and generalized parton distributions.[7]

The leading pQCD diagrams associated with the leading Fock state of the proton wave function predict that the positive helicity (quark spin aligned with the proton spin) quark distribution $q^+(x)$ scales as $(1-x)^3$, whereas the negative helicity (quark spin anti-aligned with the proton spin) quark distribution $q^-(x)$ is suppressed by $(1-x)^2$ relative to the positive helicity one, scaling as $(1-x)^5$ at large x.[3] The direct consequence of these power laws for the quark distributions is that the ratio of polarized quark distribution $\Delta q(x) = q^+(x) - q^-(x)$ over the unpolarized quark distribution $q(x) = q^+(x) + q^-(x)$ approaches 1 in the limit $x \to 1$; i.e., at large x, q^+ dominates over q^-. When this prediction is compared to the experimental data,[8–11] it is interesting to observe that, for the up quark the ratio increases with x, and seems to approach 1 at large x. However, the ratio for the down

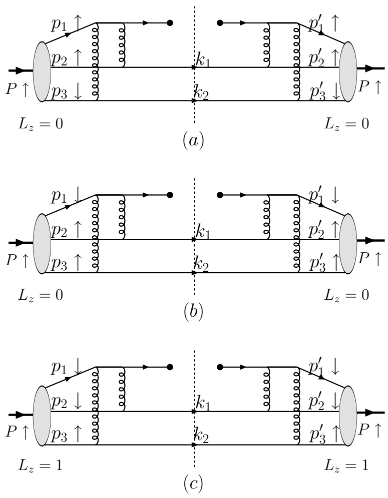

Fig. 1. *Examples of Feynman diagrams which contribute to the $q^{\pm}$ quark distributions at large x: (a) for q^+ with power contribution of $(1-x)^3$; (b) for q^- with $(1-x)^5$; (c) for q^- with $(1-x)^5\log^2(1-x)$. The wave functions at the left and right sides of the cut line in (a) and (b) represent the leading Fock state expansion with zero quark orbital angular momentum, whereas those for (c) represent the valence Fock state with one-unit of quark orbital angular momentum.*

quark is still far below 1, and remains negative for a wide range of $x \le 0.6$.[8]

In our recent study,[12] we have reexamined the large-x quark helicity distributions in the perturbative QCD framework,[3,4] and found that for the negative helicity distribution q^-, there exist large logarithmic enhancements from the $|L_z| = 1$ Fock states. With this large logarithmic modification, we can explain the discrepancy between the power-counting rule and experimental data.

2. Large-x q^- distribution

In the previous analysis, one only considered the contributions from the leading Fock state of the proton with zero quark orbital angular momentum. As we show the typical Feynman diagrams in Fig. 1(a) and (b) from this contribution, the positive helicity distribution q^+ scales as $(1-x)^3$, whereas the negative helicity distribution q^- scales as $(1-x)^5$.[3–6] In general, the contributions from the higher Fock states and the valence Fock states with nonzero quark orbital angular momentum will introduce additional suppression in (1-x).[4,6] However, the nonzero-quark-orbital-angular-momentum Fock state can provide large logarithmic enhancement to the helicity flip amplitudes. In Fig. 1(c), we show an example of a contribution from the $L_z = 1$ Fock state of proton. Because the quark orbital angular momentum contributes one unit of the proton spin, we will have difference between the total quark spin and the proton spin. If the two spectator quarks are in the spin-0 configuration, this will enhance the power-counting in the hard factor. On the other hand, in order to get a nonzero contribution, we have to perform the intrinsic transverse momentum expansion for the hard partonic scattering amplitudes,[13] which will introduce an additional suppression factor in $(1-x)$.[6] One intrinsic transverse momentum expansion comes from the propagator of momentum $(p_3 - k_2)$ will be,

$$\begin{aligned}\frac{1}{(p_3-k_2)^2} &= \frac{1}{(y_3P - k_2 + p_{3\perp})^2} \\ &\approx \frac{\beta(1-x)}{y_3 k_{2\perp}^2}\left(1 - \frac{\beta(1-x)}{y_3 k_{2\perp}^2} 2p_{3\perp}\cdot k_{2\perp}\right) ,\end{aligned} \tag{1}$$

where β is the longitudinal momentum fraction of the spectator carried by k_2, and we have kept the linear dependence on $p_{3\perp}$ in the above expansion. Only this linear term will contribute when integrating over $p_{i\perp}$: $\int k_{2\perp} \cdot p_{3\perp}(p_1^x + ip_1^y)\tilde{\psi}^{(3)} \propto (k_2^x + ik_2^y) y_3 \Phi_4(y_1, y_2, y_3)$, where Φ_4 is one of the twist-4 quark distribution amplitudes of the proton.[13,14] From the above expansion, we find that this term will introduce additional factor of $(1-x)/y_3$ in the hard factor. Similarly, we have to do the expansion in intrinsic transverse momentum associated with the wave function at the right side of the cut line, and again the expansion of the gluon propagator with momentum of $p_3' - k_2$ will introduce another suppression factor of $(1-x)/y_3'$ in the hard factor. Thus the total suppression factor from the above two expansions will be $(1-x)^2/y_3y_3'$, which gives the same power counting contribution to q^- as that from the leading Fock state with $L_z = 0$ in the above.

We thus find the contributions from $L_z = 1$ Fock state of the proton do not change the power counting for the q^- quark distribution at large x. However, the additional factor $1/y_3y_3'$ from the intrinsic transverse momentum expansions will lead to a large logarithm when integrating over y_i and y_i'. This is because, combining the above two factors with all other factors from the propagators shown in Fig. 1(c), the total dependence on y_i and y_i' for the hard factor will be

$$\sim \frac{1}{y_2 y_3^2 (1-y_2) y_2' y_3'^2 (1-y_2')} , \tag{2}$$

where we have y_3^2 and $y_3'^2$ in the denominator. On the other hand, we expect the twist-4 quark distribution amplitude to have the following behavior at the end point region: $y_3\Phi_4(y_1, y_2, y_3) \propto y_1y_2y_3$ and $y_3'\Phi_4(y_1', y_2', y_3') \propto y_1'y_2'y_3'$.[14] Thus we will have logarithmic divergences for the integrations over y_3 and y_3', for which we can regularize in terms of $\log(1-x)$ as indicated in the above propagator expansion. This will lead to a double logarithmic contribution $\log^2(1-x)$ in addition to the power term $(1-x)^5$ to the q^- quark distribution at large x.

In summary, for the negative helicity distribution q^-, the leading Fock state with zero quark orbital angular momentum $L_z = 0$ contributes to a power term $(1-x)^5$, whereas the valence Fock state with $|L_z| = 1$ contributes to a double logarithmical enhanced term $(1-x)^5\log^2(1-x)$. So, in the limit $x \to 1$, the q^- distribution will be dominated by the contributions from $L_z = 1$ Fock state of the proton, scaling as $(1-x)^5\log^2(1-x)$. In the intermediate x range, the sub-leading terms can also be important. For example in Ref.,[5] the quark helicity distributions were parameterized by the leading and sub-leading power terms and fit to the experimental data. This was later updated to account for the latest data in Ref.[15] Thus, as a first step towards a comprehensive phenomenology, we follow the parameterizations for q^+ and q^- in Ref.[5] by adding the newly discovered double logarithms enhanced contributions,

$$\begin{aligned}
u^+(x) &= \frac{1}{x^\alpha}\left[A_u(1-x)^3 + B_u(1-x)^4\right] \\
d^+(x) &= \frac{1}{x^\alpha}\left[A_d(1-x)^3 + B_d(1-x)^4\right] \\
u^-(x) &= \frac{1}{x^\alpha}\left[C_u(1-x)^5 + C_u'(1-x)^5\log^2(1-x)\right. \\
&\qquad \left. + D_u(1-x)^6\right] \\
d^-(x) &= \frac{1}{x^\alpha}\left[C_d(1-x)^5 + C_d'(1-x)^5\log^2(1-x)\right. \\
&\qquad \left. + D_d(1-x)^6\right] \ ,
\end{aligned} \tag{3}$$

where the additional two parameters C_u' and C_d' come from the logarithmic modifications to the q^- quark distribution at large x, and all other parameters refer to.[5] In the following, we will fit to the current experimental data at large x region with the above parameterizations for the valence up and down quarks.

3. Phenomenological applications

In order to demonstrate the importance of the new scaling behavior for the negative helicity distributions for the valence up and down quarks, we

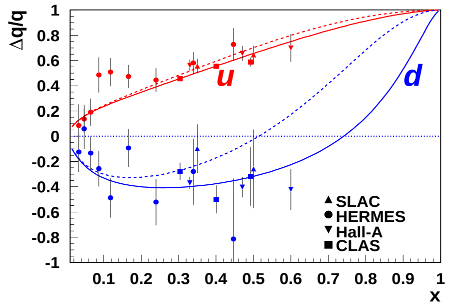

Fig. 2. *Comparison of the quark helicity distributions Eq. (3) with the experimental data, plotted as functions of x for up (the upper curves) and down (the lower curves) quarks. The circles are for HERMES data,*[10] *the triangles up for SLAC,*[11] *the triangles down for JLab Hall-A data,*[8] *the filled squares for CLAS.*[9] *The dashed curves are the predictions from,*[15] *and the solid ones are our fit results (only the large-x (> 0.3) experimental data were used in the fit).*

analyze the latest experimental data from SLAC, HERMES and Jefferson Lab, including Hall A and Hall B data.[8–11] We will keep the original fit values for other parameters[15] except the two new parameters: C'_u and C'_d. We only use the experimental data in the large-x region, i.e., $x > 0.3$, where the sea contribution is not significant. From our fit, we find the following values for C'_u and C'_d,[12]

$$C'_u = 0.493 \pm 0.249, \qquad C'_d = 1.592 \pm 0.378 \; , \tag{4}$$

The minimum of the functional χ^2 is achieved at $\chi^2 = 11.4$ and $\chi^2/DOF = 1.14$. We further notice that the additional two terms in Eq. (3) do not change significantly the sum rules for the up and down quarks, such as the Bjorken and momentum sum rule, which are essential for constraining the parameters in Refs.[5,15]

In Fig. 2, we show the above fit. We plot the ratios of the polarized quark distributions Δq over the unpolarized quark distributions q as functions of x for both up and down quarks, compared with the experimental data. From these comparisons, we find that the ratio for the up quark $\Delta u/u$ can still be described by the parameterization based on the original power counting rule for u^+ and u^-.[15] However, for the down quark we have to take into account a large contribution from the newly discovered term for the negative helicity distribution d^-; the difference between our result and the original parameterization[15] becomes significant at large x. Another important prediction of our fit is that the ratio of $\Delta d/d$ will approach 1 at extremely large x, and it will cross zero at $x \approx 0.75$. It will be interesting to check this prediction in future experiments, such as the 12 GeV upgrade of Jefferson Lab.

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